GEODETIC MONITORING AND MODELLING OF SURFACE DEFORMATIONS ALONG MAIN GAS PIPELINE ROUTE

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Abstract. This study focuses on geodetic monitoring and modelling of surface deformations along the route of a main gas pipeline, emphasizing its critical role in ensuring the safety and reliability of energy infrastructure operations. With gas pipelines being vital to energy supply networks, continuous monitoring of their condition is particularly necessary in geologically unstable areas. The research highlights the relevance of deformation monitoring in addressing the challenges posed by ground subsidence and displacement, which can jeopardize the integrity of pipelines and surrounding infrastructure. The object of the study is the gas pipeline segment located near the mining operations of the "Heroes of Space" mine within the Verbkiv territorial community in the Dnipropetrovsk region in Ukraine. Fieldwork included geodetic surveys performed using advanced GNSS technologies, enabling high-precision monitoring of earth surface movements. A network of 34 benchmarks, installed at 20-meter intervals along the gas pipeline route, served as the basis for periodic satellite observations. Data collected during these observations were processed and analysed to determine both horizontal and vertical displacements of the monitoring points. The results provided a comprehensive dataset for modelling the subsidence of the earth surface and assessing its potential impact on the gas pipeline. The study demonstrates the effectiveness of geodetic monitoring as a tool for identifying risks associated with deformation processes. The findings contribute to developing predictive models for surface subsidence and displacement, which are essential for implementing timely maintenance and ensuring the long-term stability of energy infrastructure in areas prone to ground movement.

Keywords: geodetic monitoring, modelling, GNSS technologies, surface, deformations.

Introduction

The safe and efficient operation of main gas pipelines is critical to ensuring energy security and minimizing environmental risks. These pipelines often traverse vast and geologically diverse terrains, making them susceptible to surface deformations caused by natural and anthropogenic factors. Geodetic monitoring and modelling have emerged as indispensable tools for assessing and predicting surface deformations along pipeline routes. By leveraging advanced geospatial technologies, such as satellite-based interferometry, GNSS (Global Navigation Satellite Systems), and terrestrial surveying techniques, engineers and geoscientists can detect ground movements with millimetre-level precision. This capability is essential for identifying potential hazards, such as landslides, subsidence, or tectonic activity, which could compromise pipeline integrity and lead to catastrophic failures [1-3].

This article explores the methodologies and applications of geodetic monitoring and modelling in the context of surface deformations along main gas pipeline routes, highlighting their role in ensuring the long-term safety and reliability of these critical infrastructure systems.

Materials and methods

The section of the gas pipeline under investigation is located in the Pavlohrad-Petropavlivsk geological and industrial region of the Donbas. In terms of geological structure, the area is associated with the southeastern part of the Novomoskovsk-Petropavlivsk monocline, situated on the northeastern slope of the Ukrainian crystalline shield and extending along the southwestern edge of the Dnieper-Donets Basin. This region is characterized by complex geological conditions, making it essential to monitor surface deformations to ensure the stability and safety of the gas pipeline infrastructure.

To address these requirements, a dedicated monitoring station has been established on the gas pipeline branch section affected by mining activities. This section falls within the influence zone of the 960th longwall panel of the Heroes of Cosmos Mine. The monitoring station consists of a profile line of ground benchmarks installed along the route of the gas pipeline branch. Within the influence zone of the 960th longwall panel, a segment of the gas pipeline branch includes 34 ground benchmarks positioned along the profile line of the monitoring station. These benchmarks are critical for tracking ground movements and assessing potential deformations caused by mining operations, ensuring the integrity and safe operation of the pipeline (Fig 1).

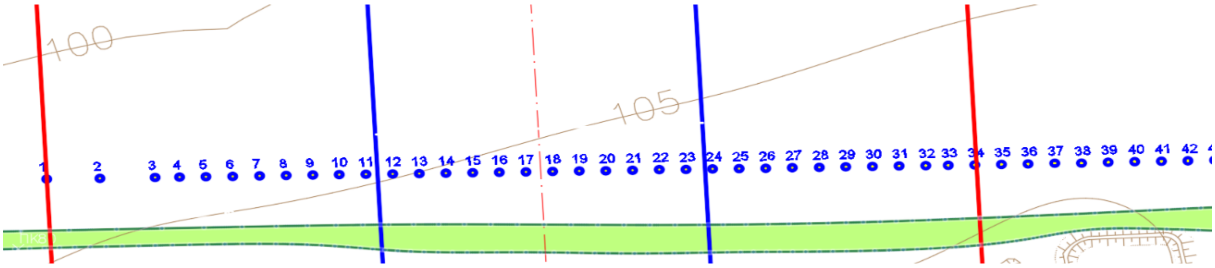

Fig. 1. **Scheme of assigned rappers**

The ground benchmarks of the monitoring station are installed at intervals of 20 meters along lines located 15 meters from the projection of the gas pipeline axes onto the ground surface. As reference benchmarks for the monitoring station, two ground benchmarks are established outside the influence zone of mining activities – at the beginning and end of the profile line. These reference benchmarks are positioned at distances of no less than 50 meters and 100 meters from the start and end of the profile line, respectively. This configuration ensures stability and reliability of the reference points, which are critical for accurate deformation monitoring [4-6].

Geodetic monitoring of the deformation of the main gas pipeline was conducted using GNSS equipment from Leica Geosystems, specifically the Leica Viva GS08 Plus GNSS receiver and the Leica Viva CS10 field controller. These high-precision instruments enable millimetre-level accuracy in measuring ground movements, providing essential data for assessing the impact of mining activities and ensuring the structural integrity of the gas pipeline. The use of advanced GNSS technologies underscores the importance of precise and reliable monitoring in mitigating risks associated with surface deformations.

In the context of geodetic monitoring and modelling of surface deformations along the route of a main gas pipeline, the foundational works by Brunner F. K., Coleman R. and Hirsch B. [7], as well as Caspary W. F. [8], have significantly contributed to the theoretical and methodological base of deformation analysis. Brunner et al. [7] conducted a comparative study of computational methods for determining crustal strains from geodetic measurements, highlighting the strengths and limitations of various analytical approaches. Their work provided crucial insights into the accuracy and reliability of strain estimation, which is essential when analyzing stress accumulation or structural integrity along linear infrastructures such as pipelines.

Hein G. and Kistermann R. [9], as well as Malzer et al. [10], expanded on the understanding of vertical and non-tectonic deformations by mathematically modelling environmental and anthropogenic factors that can influence geodetic measurements. These studies are particularly relevant for isolating local effects unrelated to tectonic processes that may still pose risks to pipeline infrastructure. Margrave G. F. and Nyland E. [11] further advanced the field by applying generalized inverse methods to interpret strain from repeated geodetic surveys, offering adaptable tools for long-term monitoring. Complementing these contributions, Holian et al. [12; 13] emphasize the integration of scientific modelling with economic and policy mechanisms, particularly in the context of sustainable development and infrastructure investment. Although primarily focused on the forest sector, their work demonstrates the importance of financial planning and innovative management practices, which can be extrapolated to the strategic planning of geodetic monitoring systems for large-scale engineering projects like gas pipelines.

Results and discussion

In the context of the gas pipeline route to Ternivka, which is positioned perpendicular to the direction of movement of the 960th longwall panel, the largest values of calculated displacements and deformations of the earth’s surface are observed after the completion of the subsidence process. During the active mining phase, deformations along the gas pipeline route gradually increase, maintaining a consistent direction (without changing the sign of deformation). These deformations reach their maximum magnitude approximately 1.4 months after the longwall face has stopped advancing, as the ground stabilizes, and the full extent of subsidence becomes apparent. The outcomes of the calculated displacements and deformations of the land surface along the gas pipeline route are presented in Table 1.

Table 1

Results of calculation of estimated displacements and deformations of the earth surface along the experimental route of the main gas pipeline

Point No	Subsidence	Tilt	Curvature	Horizontal Deformations	Horizontal Shifts
	mm	$x10^{-3}$	$x10^{-6}$	$x10^{-3}$	mm
0	0	0	0	0	0
1	9	0.4	12.1	0.7	24
2	14	0.5	16.6	0.95	34
3	30	1.1	31.1	1.79	71
4	44	1.4	36	2.06	90
5	88	2.4	49.8	2.86	151
6	113	2.8	51.9	2.98	178
7	195	4.1	55	3.16	259
8	233	4.5	51.3	2.95	285
9	356	5.6	35.1	2.01	351
10	403	5.8	25.4	1.46	364
11	557	6.1	-5.5	-0.32	383
12	672	5.9	-27.9	-1.6	374
13	768	5.3	-45.3	-2.6	333
14	856	4.4	-61.1	-3.51	282
15	924	3.4	-70.2	-4.04	214
16	987	2.3	-78.4	-4.5	144
17	1004	1	-80.8	-4.64	64
18	1013	-0.3	-83.9	-4.77	-17
19	997	-1.6	-81.4	-4.63	-98
20	961	-2.8	-76.5	-4.35	-175
21	894	-3.9	-67.8	-3.85	-245
22	815	-4.9	-54.9	-3.12	-305
23	726	-5.7	-38.7	-2.2	-357
24	617	-6	-17.5	-1	-378
25	500	-6.2	5.5	0.31	-387
26	404	-5.8	25.8	1.47	-364
27	310	-5.4	44.9	2.56	-336
28	232	-4.5	52.4	2.98	-284
29	161	-3.7	57	3.24	-231
30	136	-3.3	55	3.13	-204
31	70	-2	43.9	2.5	-125
32	43	-1.4	34.9	1.98	-87
33	25	-0.9	25.3	1.44	-57
34	0	0	0	0	0

From the data provided, the largest subsidence value is 1013 mm at point 18, which corresponds to the maximum vertical displacement of the surface. This point also exhibits the highest curvature of -83.9 $x10^{-6}$, indicating significant bending of the ground. Additionally, the largest horizontal deformation of -4.77 $x10^{-3}$ and the greatest horizontal shift of -387 mm (at point 25) are observed in the latter part of the profile line, reflecting the substantial lateral movement of the ground.

Conversely, the smallest values of subsidence, tilt, curvature, horizontal deformations, and horizontal shifts are found at the starting and ending points of the profile line (points 0 and 34), where all values are zero. This is expected, as these points are located outside the influence zone of mining activities and serve as stable reference points for monitoring (Fig 2).

The data demonstrates that the most significant deformations occur in the central section of the profile line, where the influence of the 960th longwall panel is most pronounced. These findings underscore the importance of continuous monitoring and the implementation of mitigation measures to ensure structural integrity of the gas pipeline, particularly in areas experiencing the highest levels of deformation.

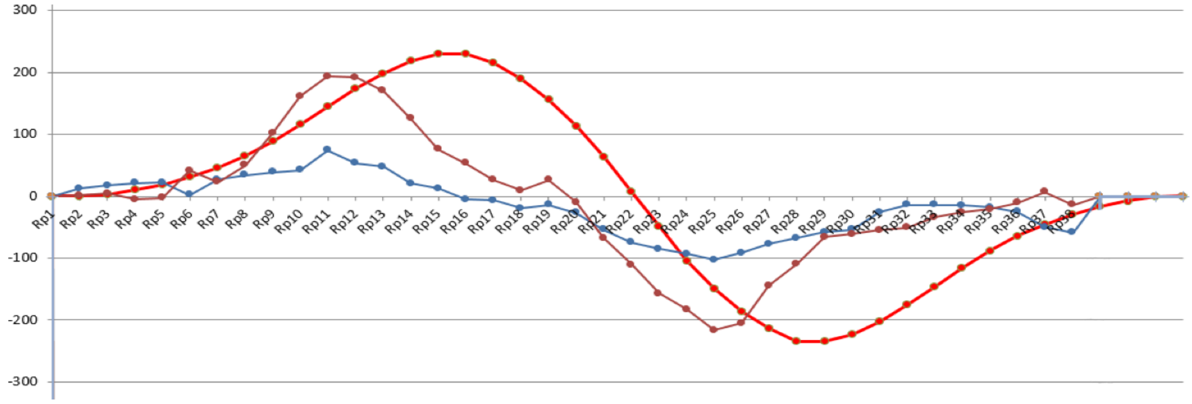

Fig. 2. **Graphs of horizontal displacements of the earth surface from the flow of 960 lava: created by the authors based on the results of monitoring 3 observations**

Based on the monitoring results, a three-dimensional model of land surface subsidence caused by the influence of the 960th longwall panel was developed using the software product “Forgery” (Fig. 3).

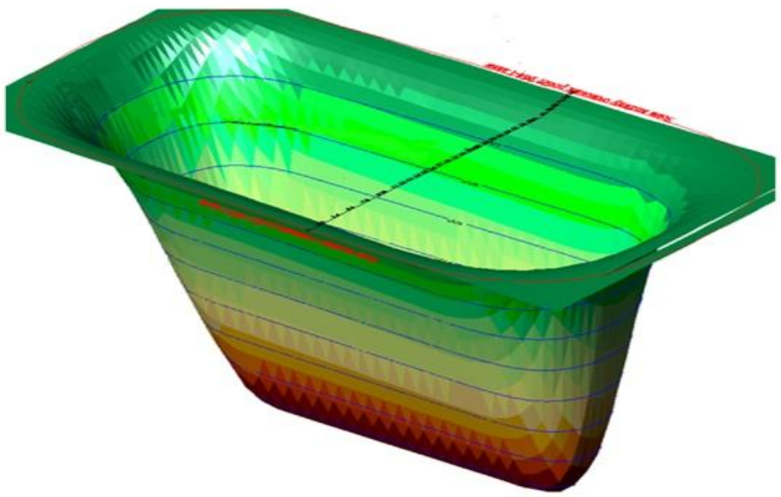

Fig. 3. **Three-dimensional (off-scale) model of land subsidence due to the impact of 960th lava**

For a more detailed representation of the deformation of the earth surface along the main gas pipeline branch to the city of Ternivka, located within the Verbkivka territorial community of the Dnipropetrovsk region and within the influence zone of mining operations at the “Heroes of Space” mine, deformation graphs for specific observation points were created. These graphs illustrate the behaviour of the ground surface at Rp 8, Rp 17, and Rp 18 over time, providing a clearer understanding of the deformation dynamics in this critical area (Fig. 4).

These graphs provide a visual representation of the deformation process at key observation points, emphasizing the spatial and temporal variability of ground movements. They underscore the importance of continuous monitoring and the need for proactive measures to mitigate the impact of mining activities on the gas pipeline infrastructure. The data from these graphs can be used to refine predictive models and develop strategies to ensure long-term stability and safety of the pipeline.

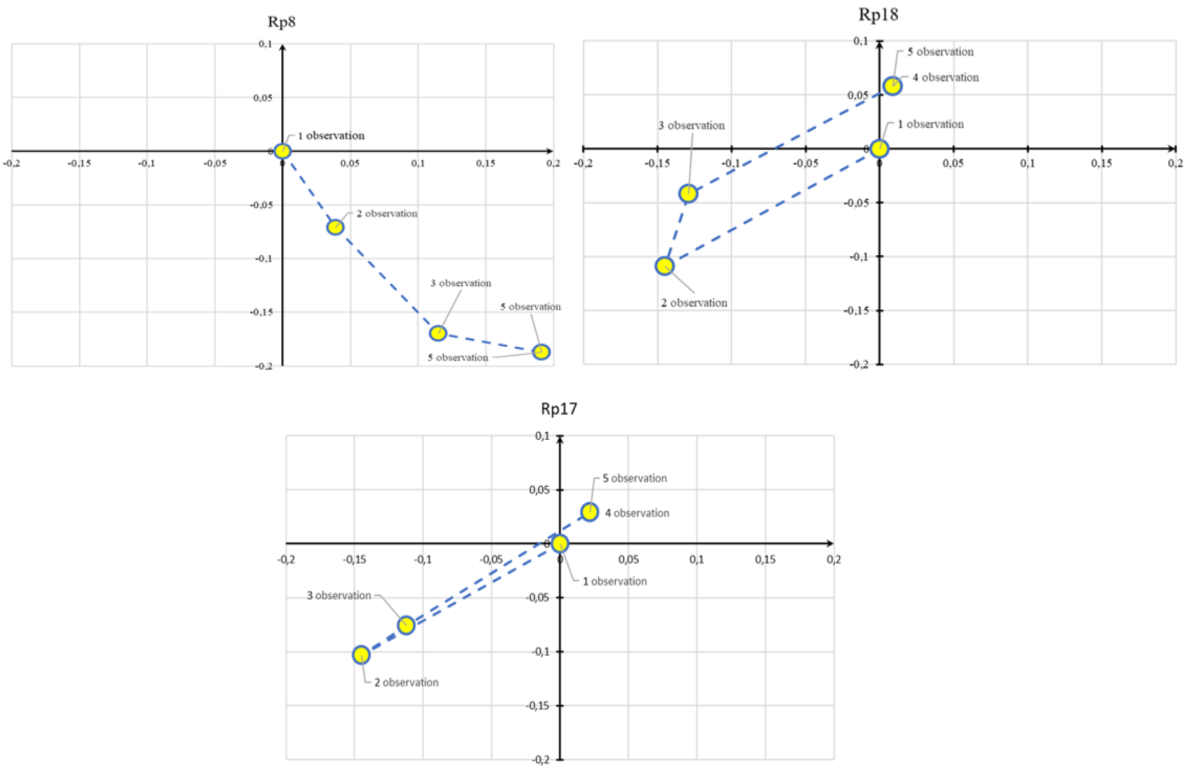

Fig. 4. **Horizontal displacement graphs Rp 8, Rp 17, Rp 18**

Conclusions

1. The observational data from the monitoring stations along the gas pipeline branch to Ternivka reveal a clear spatial pattern of surface deformations, with the highest subsidence values reaching 1013 mm at Rp 18 and significant horizontal shifts of up to -387 mm at Rp 25. These deformations are concentrated in the central part of the profile line, where the influence of the 960th longwall panel is most pronounced. The data also shows that the deformation process is not uniform, with varying rates of subsidence, tilt, and curvature across different points. For instance, Rp 8 and Rp 17 exhibit gradual increases in deformation, while Rp 18 experiences a more abrupt change, reflecting the complex interaction between mining activities and the geological conditions of the area.
2. Furthermore, the analysis of horizontal deformations and curvature highlights the potential risks to the structural integrity of the gas pipeline. The maximum horizontal deformation of -4.77 $x10^{-3}$ and curvature of -83.9 $x10^{-6}$ at Rp 18 indicate severe ground bending, which could lead to pipeline strain or failure if not addressed. The observational data also confirms that deformations stabilize approximately 1.4 months after mining activities cease, providing a critical timeframe for post-mining monitoring and maintenance. These findings emphasize the importance of integrating geodetic monitoring data with predictive models to develop effective risk mitigation strategies and ensure safe operation of the gas pipeline in mining-affected regions.

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Author contributions

Conceptualization, Ivan Openko and Mykyta Kozhemiako; methodology, Ivan Openko and Mykyta Kozhemiako; software, validation, Oleksandr Shevchenko; formal analysis, Olha Tykhenko; investigation, Ivan Openko and Oleg Tsvyakh; data curation, Ivan Openko, Viktor Podliegaev, Yevheniia

Kryvoviaz; writing original draft preparation, Ivan Openko and Ruslan Tykhenko; writing – review and editing, Ivan Openko and Mykyta Kozhemiako; visualization, Iryna Kolhanova; project administration, Ivan Openko; funding acquisition, Oleg Tsvyakh. All authors have read and agreed to the published version of the manuscript.

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